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TOPEX / POSEIDON FLIGHT BATTERY OPERATIONS

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ABSTRACT

TOPEX/POSEIDON batteries continue to operate and support science loads after six years of operations. Concerns about cell quality have been dispelled through ground test and flight operations. The planned eight-year extended mission will likely be met. Estimated time-to-failure is over ten years. Operations have been performed with a rigorous approach to reducing overcharge and controlling battery peak charge rate to insure this reliability.

I. INTRODUCTION

Since it's launch in August of 1992, the TOPEX / Poseidon mission has been mapping the height of the oceans, providing new knowledge of the interaction between earth's oceans and our global weather patterns. The spacecraft was built by Fairchild and uses a single Modular Power Subsystem, build by Macdonald Douglas. The MPS contains three 50 Ampere-Hour NASA standard batteries. Gates Energy Products built the cells used in the 22-cell batteries. The 830-mile, low-earth-orbit mission is at a high inclination angle. The orbital profile and precision ground track have important consequences on the batteries. The high inclination orbit gives a seasonal change from full sun up to a maximum of 12.5% Depth-of-Discharge (DOD) at 34.5 minutes of spacecraft night. A typical eclipse season is shown below, with eclipse length and minimum End-of-Night (EON) voltage plotted. The spacecraft typically sees four occultation seasons per year, two each with two humps, as show below, and two with single humps. Between occultation periods is several weeks of full-sun.

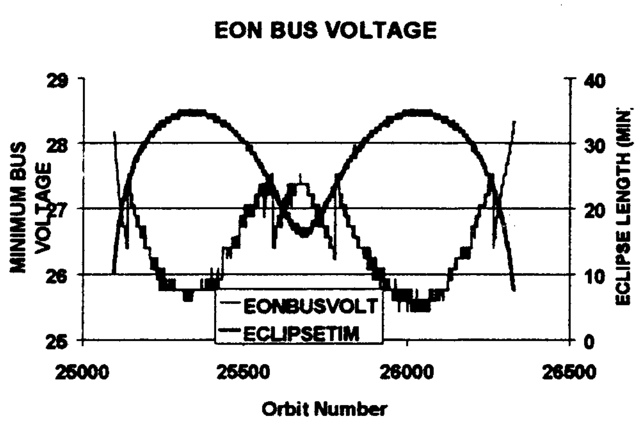


Figure One – Typical Occultation Season

II. BATTERY OPERATIONS

A.) VT CONTROL

NASA VT level 2 up through level 4 are used depending upon the length of the spacecraft night. VT level 2 is used for full sun, with VT level 3 for lower DOD's, while VT level 4 for the higher DOD's.

VT SWITCHING SCHEME

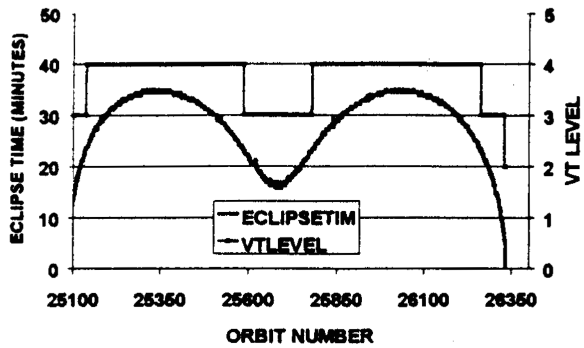


Figure Two – VT Curve Switching

The amount of time spent at VT#4 has been increase in the last year. At launch the value of 28-minute eclipses was used for the VT#3 to VT#4 switching. That has been moved to 24 minutes, with further adjustment to 20 minutes being used on occasion. Increasing the VT level to #5 or higher is being reserved for later in the mission.

B.) PEAK CHARGE CURRENT

Peak charge current was determined to be an important parameter before launch, and has been controlled throughout the mission. While MPS equipped spacecraft have traditionally been allowed to operate with maximum solar array power for recharging, this practice was associated with premature battery failures on some other NASA satellites.

The range for peak-charge current was set at 13 to 20 amperes at launch. This range is achieved by offsetting the solar array, using a fixed bias. The Solar array offset has been changed repeated throughout the mission to account for solar array degradation. Recently, the range for peak-charge current has been modified to allow increase battery peak-charge current levels. The new range is 17 to 22 amperes. This is still considerably below values traditionally used, which are known to exceed 30 amperes on other MPS equipped satellites. The single excursion to 27 amperes is due to a sun pointing safehold that occurred.

The lowest peak-charge currents are achieved in the lowest DOD orbits, where the shorter time in earth shadow allows for less array cooling. The short eclipses occur at the entry and exit from occultation seasons, and the saddles between seasons. These seasons are dictated by the beta prime angle in the TOPEX orbit. The highest peak charge rates are seen in the highest DOD orbits, which occur at low beta primes. DOD maxima are always found at beta prime angle equals zero.

BATTERY PEAK CHARGE CURRENT

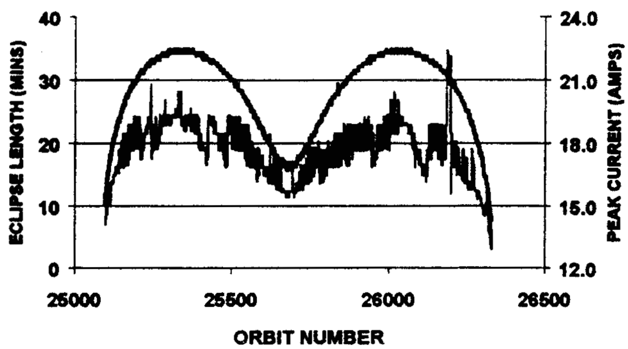


Figure Three – Peak Charge Current

Other variations in peak charge current noticeable on the plot are due to yaw steering versus fixed yaw operation, operating in fly forward versus backwards modes, and lunar avoidance maneuvers, discussed below.

Battery charge acceptance is worst in low DOD's orbits, as evidenced below in the differential voltage data. A high peak charge rate is not tolerated well in a low DOD orbit, as shown in a previous publication (1). These problems are made worse at high VT levels, cold temperatures, and cells containing negative electrodes with marginal operating characteristics.

C. DIFFERENTIAL VOLTAGES

The charge acceptance of the batteries has been studied by analyzing the differential voltages. High DOD orbits are accompanied by differential voltage spikes at the end-of-night (EON). These EON differential voltage (dV) spikes are referred to as tail-ups. They are caused by differences in the rate of cells voltages decline near the boundary between upper and lower discharge plateau regions. Only after a two-plateau discharge curve, commonly called a memory effect, has begun to develop, are these dV signatures seen. Lower than optimal charging increase these end-of-night tail-ups in the short term. Higher charge rates or VT levels diminish the tail-ups, but can lead to differential peaks at the transition to peak power charging. These are called peak power cusps. They are an indication that charge acceptance is compromised. The mechanism for peak power cusps is most likely a variation in the over-voltage at the negative electrodes of different cells. In severe cases, where overcharge protection is insufficient, this can lead to hydrogen production. High charge rates can increase the peak power cusp's magnitude. Avoiding high charge rates for low DOD orbits prevents this problem.

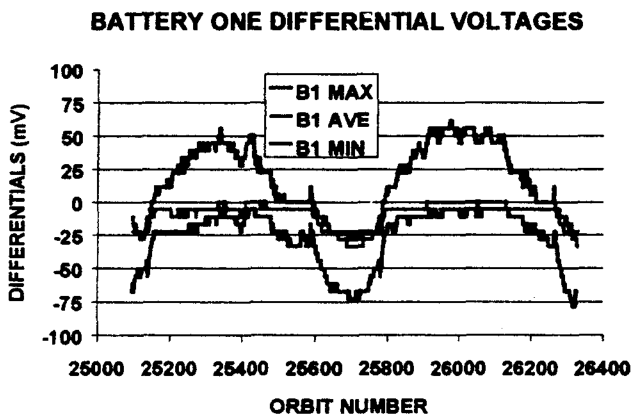


Figure Four – Differential Voltage Statistics

TOPEX's high inclination orbit mission typically yields low charge rates at the lowest DOD's. Too low a charge rate can lead to low charge acceptance, low and variable SOC's. In this case, the differential voltages can also develop an offset, where the differential voltage channel does not return to a zero reading by the end of charge. These offsets are always accompanied by high peak values. A differential offset is an indicator that charging parameters should be adjusted. Worst-case peak differential voltages for TOPEX have been limited to 76 millivolts, and offsets have been less than 28 millivolts. These levels are considered low, but are steadily increasing.

III. THE EFFECT OF MISSION EVENTS

A.) SAFEHOLD / RECONDITIONING

In August of 1996 a sun pointing safehold was initiated when an electronics failure in the Solar Array Drive Electronics failed, allowing a large error in solar array angle. The spacecraft loads pulled the battery SOC down to a level where a partial in orbit reconditioning was achieved. The batteries discharged down to 24.4 volts and around 35% DOD. The battery temperature went just over 10 degrees Celsius, compared to the normal level of 10 Celsius. The effects of this inadvertent reconditioning on EON voltage lasted for almost one year, as seen below.

B.) FIXED YAW STEERING

Controlling the battery peak charge current has been made more complex by the use of a fixed yaw steering mode. Near beta prime angle equals zero this attitude control mode is used to vary the drag experienced by the solar panel. This helps maintain the precision ground track without use the propulsion system. These changes effect both solar array output and the heater loads, and peak-charge current. The amount of time spent in this mode varies with each occultation season, depending upon the estimates of the effect on the ground track. The allowable range for fixed yaw operation is determined by performance predictions for battery peak charge rate. This has been so successful that the battery peak charge rate can be maintained within its flight allowable, while maintaining the precision ground track for over three years, without need to perform a maneuver. Recently, more aggressive maneuvers to maintain ground track have been required, due to increased solar activity. Fixed yaw operations at higher levels of beta prime angle have been performed, out to greater than 30 degrees, compared to the normal limit of 21 degrees. This would normally create problems with peak charge current dropping to around 13 amperes per battery. To compensate, temporary solar array offset changes are required. The nominal offset of 48.5 degrees used in 1998 has to be switched to approximately 42.5 degrees to accommodate the extended fixed yaw operation.

C.) STAR TRACKER EFFECTS

Difficulties with star trackers have forced the program to adopt a series of lunar avoidance maneuvers. These problems have been attributed to radiation damage. The goal of these maneuvers to prevent the moon from coming into the field of view of the star scanner. These possible lunar intrusions occur approximately every two weeks. These maneuvers vary in design, but often use a fixed yaw offset of 15 degrees, an early yaw flip, or an extended fixed yaw operation. Further compensation for these maneuvers is also required. These non-standard operations each require analysis to verify that DOD, recharge energy, and maximum charge rate guidelines are not violated. They typically require a solar array offset adjustment for a single day. The ability to predict the compound angle on the solar panel, the temperature of the array, and the resulting battery peak charge current for each event is a challenge for the ground analysis team. It has also forced the spacecraft into operating in a wider envelope. These maneuvers will be ended when both star-scanners are no longer useable for attitude control. Another attitude control mode will be used at that time.

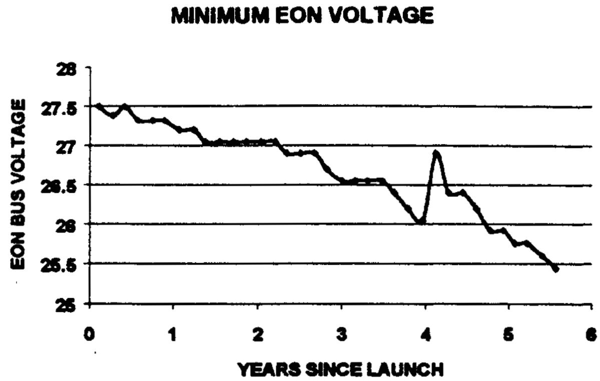
VI. SPACECRAFT PERFORMANCE

A.) END-OF-NIGHT VOLTAGE

End-of-night voltage for each of the maximum DOD points for the mission is plotted below. The effect of the unintended reconditioning is clearly visible as a sharp increase in EON voltage. The rather sharp decline in the latter part of the chart is expected to slow, as the effect of a second plateau buoys the lowest potentials.

The altimeter will perform a load shed at 24.4 volts, but the spacecraft bus is tolerant of voltages below 24.0 volts.

Figure Five – Minimum EONV Trend



B.) RECHARGE FRACTION

The recharge fraction trend across the mission is largely stable after a slight decline in he first two years. The chart below is a trend for the maximum DOD orbits only. Higher C/D ratio's are seen for lower DOD orbits. Other methods for measuring overcharge are also employed, including absolute ampere-minutes of overcharge, which is typically 24 amp-minutes or lower.

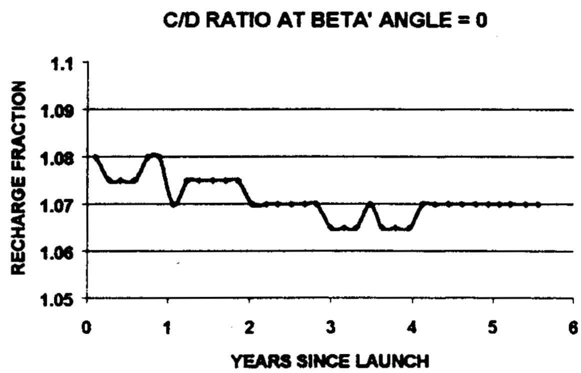


Figure Six – C/D Ratio Trend

C.) TEMPERATURE CONTROL

The temperature control of the batteries has been excellent, with differentials within the accuracy and resolution of the telemetry system. Increases amount to about 0.1 degrees per year.

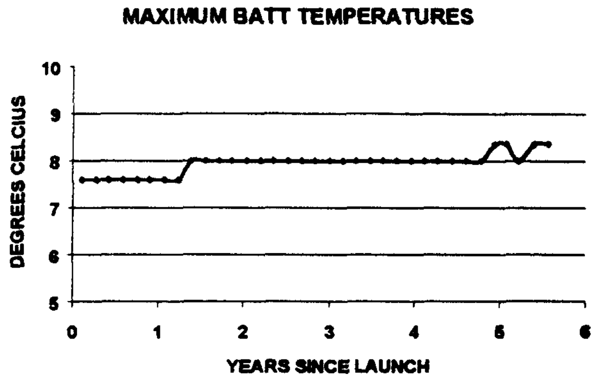


Figure Seven – Battery Temperature

D.) LOAD SHARING

Load sharing between the batteries has been excellent. With the accuracy and resolution of the telemetry channels, it is not possible to detect any changes since launch.

E.) DIFFERENTIAL VOLTAGES

The differential voltage channels have been the most active, indicator of battery performance changes, but they are the least important, as they are only an indicator, and not a subsystem operating parameter.

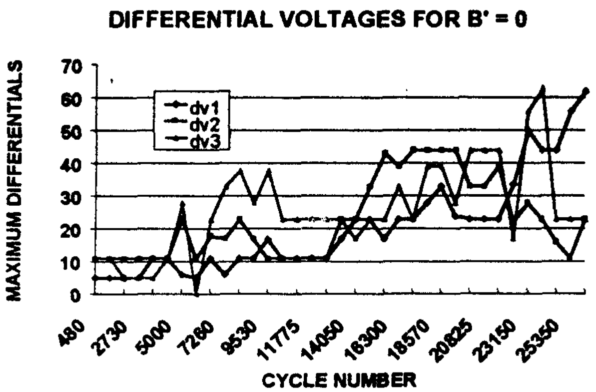


Figure Eight - Differential Voltage Trend

F. PEAK CHARGE RATES

The peak-charge rates at beta prime angle equals zero has been controlled accurately throughout the mission, with only a few exceptions. Such an example is the safehold, which caused sun pointing and a solar array offset of zero. This was well tolerated by the batteries, as the beta prime angle at the time gave long eclipses. The greater challenge is controlling the range of rates within each occultation season. This in one of the most challenging aspects of TOPEX battery operations

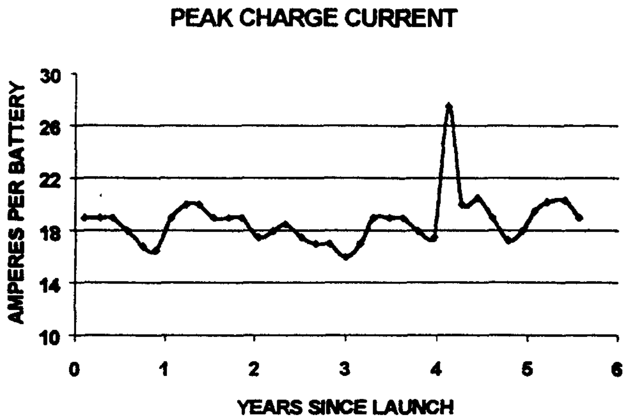


Figure Nine – Peak Charge Rate

V. END-OF-LIFE PREDICTIONS

The time to failure for the spacecraft batteries has been estimated to be ten years. This number is supported by several analyses. The first is the EONV prediction shown above. This curve was developed using the Crane database, and represents test data, adjusted to account for TOPEX specific flight parameters.

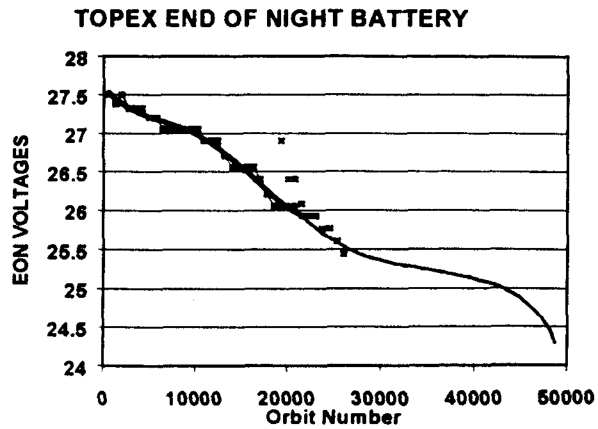


Figure Ten – EONV Predict

The other analysis was done using the empirical life predictions of Lim and Thaller(2). Both predictions exceeded the desired mission life of eight years by a considerable margin, indicating a high confidence in supporting an eight-year mission. Further analysis indicates that the eight-year mission could even be supported with the loss of one battery at any time after 5 years into the mission. This analysis used the same DOD, temperature, cycle life relationships found in reference (2), but with life being allocated at two different DOD, relating to two and three battery operation

VI. ACKNOWLEDGEMENTS

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VII. REFERENCES

(1.) Deligiannis, F, "NASA Battery Testbed Capabilites and Results", 1994 NASA Aerospace Battery Workshop: NCP 3292, February 1995, pp.323.

(2.) Deligiannis, F., "NASA Battery Testbed: A Designed Experiment for the Optimization of LEO Operational Parameters", 1995 NASA Aerospace Battery Workshop: NCP 3325, February 1996, pp.579.

(3.) Lim, H., and Thaller, L., "A Prediction Model of the DOD effect on the Cycle Life of a Storage Cell", 22nd IECEC Conference Proceedings, August 1987, pp. 751.